Chapter Seven

Culvert, Rigid Frame and Arch Design

7.1 INTRODUCTION

Culverts are typically rectangular, circular, or elliptical pipe structures which are buried and designed when flowing full to be submerged and under hydraulic pressure. They are usually used to drain tax ditches or small streams. Most large culverts are constructed with headwalls, wingwalls, cutoff walls, and scour aprons. See Figure 7-1 for a typical culvert. This chapter will discuss various types of culverts that are used by DelDOT. For related issues see Chapters 3, 5, and 6.

Types of culverts used in Delaware include pipes, boxes, rigid frames, and arches. Culverts can be constructed of concrete, steel, aluminum, or high-density polyethylene. Most small culverts in Delaware are constructed with round or elliptical pipes. Only culverts or a series of culverts with a total opening size of 20 ft^2 [1.86 m^2] or greater are classified as bridges in Delaware. Culverts with total opening sizes smaller than 20 ft^2 [1.86 m^2] are not included in the Department's bridge inventory. For openings larger than 20 ft^2 [1.86 m^2], box culverts, rigid frames, or arches are usually required. Culverts of 20 ft^2 [1.86 m^2] or greater require load ratings per Chapter Four.

The use of boxes or arches vs. larger or multiple pipes is based on a number of factors, including hydraulic efficiency, compaction around the structure, height of fill required, and total width of multiple cells. In most cases, a three-sided frame or arch is preferred to provide a natural stream bottom and low-flow channel. However, these require scour protection. A typical culvert with a natural stream bottom and scour protection is shown in Figure 7-1. For the flat topography typical of most of Delaware, taller culverts are unsuitable. In these conditions, elliptical pipes, arch pipes, or boxes may be desirable. In any case, culverts should be designed to economically meet the hydraulic and environmental demand of the location.

7.2 GENERAL POLICY

Culverts shall be designed to meet the current and future hydraulic and transportation needs of the location. All culverts shall be constructed of concrete under Interstate, US, and Delaware routes. Designers may consider using structural plate or polyethylene culverts to reinforce/reline deteriorated culverts in lieu of replacement.

This section will discuss the Department's policy related to culvert hydraulics, foundations, wingwalls, cutoff walls, scour aprons, etc.

Figure 7-1a
Box Culvert Example - Section

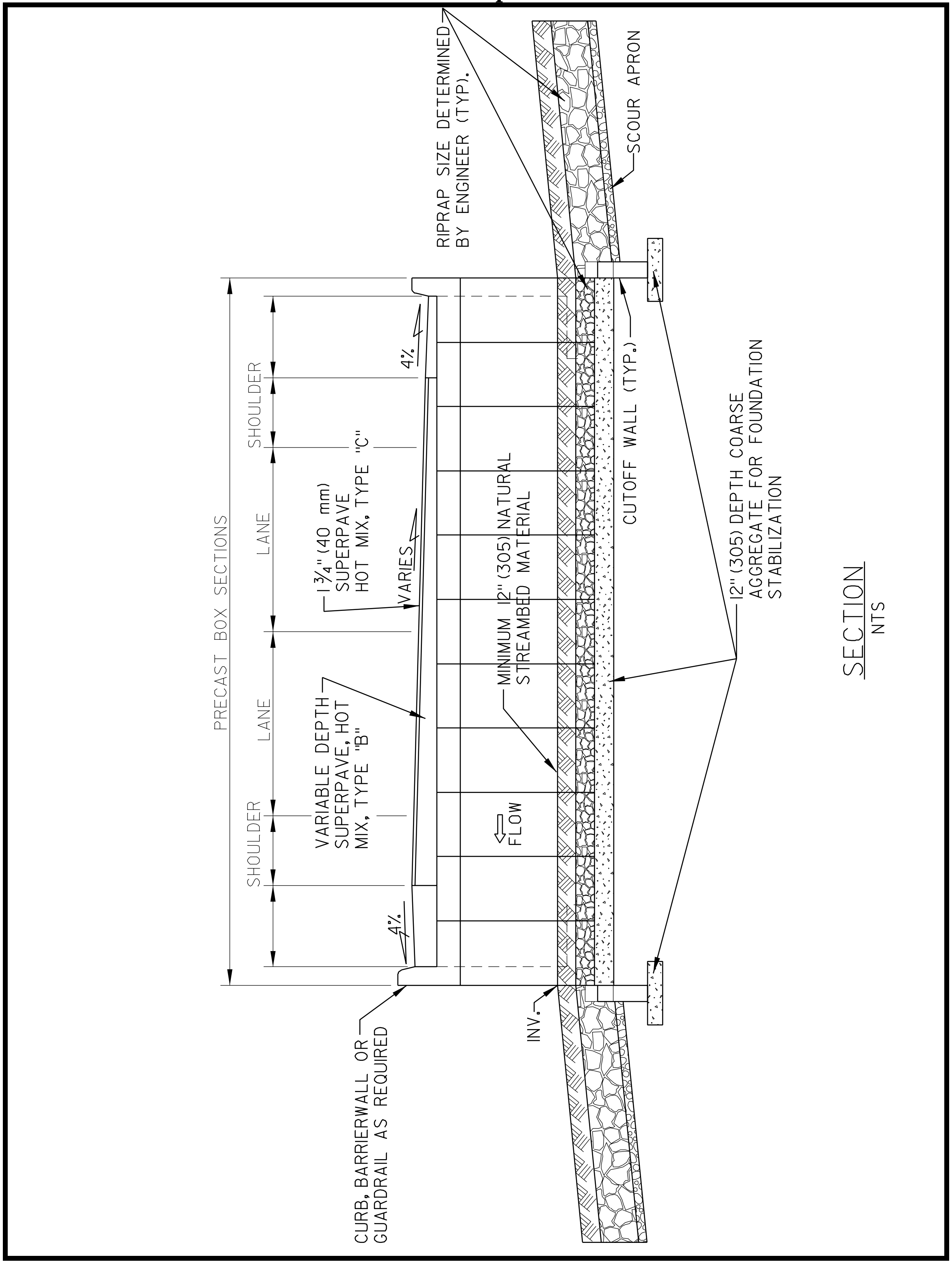
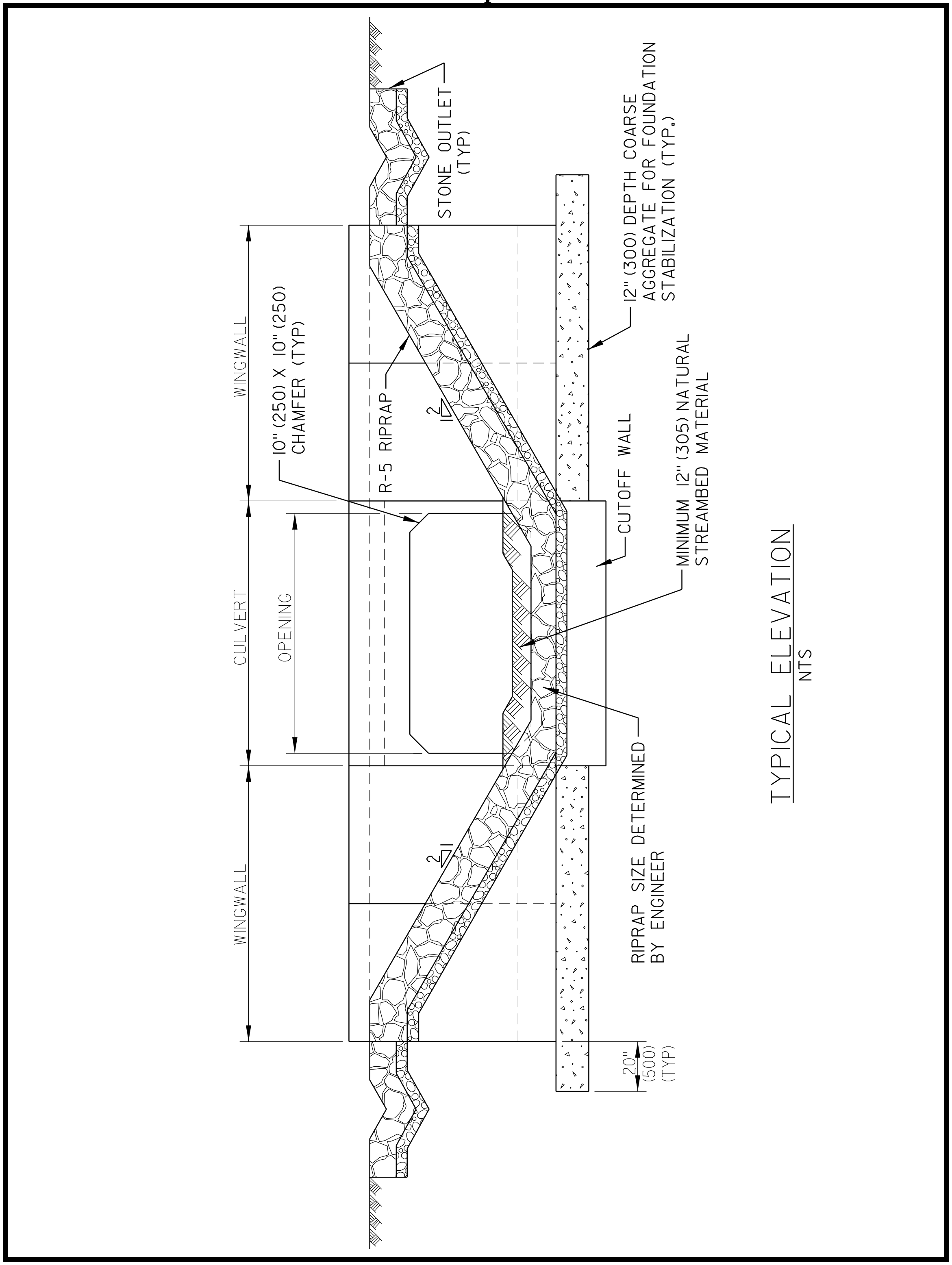


Figure 7-1b
Box Culvert Example - Elevation



7.2.1 CULVERT HYDRAULICS

Refer to Chapter Three of this manual.

7.2.2 FOUNDATION DESIGN

Sub-surface investigations shall be conducted and analyzed to determine allowable load bearing capacity. Sub-surface investigations and design shall be carried out in accordance with Chapter 6. Coarse aggregate for foundation stabilization may be placed under culverts, typically 1 ft [300 mm] thick. The coarse aggregate shall extend a minimum 1.5 ft [450 mm] beyond all sides of the culvert.

At least 3 ft [0.9 m] shall be provided between multiple round, elliptical, and pipe arch culverts to allow for proper compaction. This spacing may be reduced if flowable fill is used. Due to the high corner pressure of pipe arches, special bedding material shall be specified, such as compacted borrow type C.

Requirements for excavation, backfill, and bedding are contained in the DelDOT *Standard Specifications*, Section 207, Excavation and Backfilling for Structures. Backfill shall meet the requirements of borrow type C or borrow type B in wet conditions.

7.2.3 HEADWALLS

Headwalls for pipes consist of an entire retaining wall structure around the inlet and outlet of the pipe, including the footing. Headwalls shall be considered on larger pipes for hydraulic efficiency, stability, and reduced need for right-of-way acquisition.

For a Reinforced Concrete Box (RCB), headwalls refer to that portion of the structure mounted on top of the box at the outlet and inlet to contain the earth on the top and around the culvert.

Where warranted, headwalls shall have concrete traffic barriers mounted on top of them.

7.2.4 WINGWALLS

Wingwalls are typically cast-in-place construction but can be precast in some cases. If precast wingwalls are specified, they must be designed to be self-supporting, not relying on the connection to the culvert for stability; however, proper connection to the culvert must be provided. A typical precast wingwall-to-culvert and wingwall-to-wingwall detail is shown in Figure 7-2. For retaining wall design criteria, see Chapter 6.

Wingwalls are called “flared” when the axis of the wingwall forms an angle with the centerline axis of the box. “Straight” wingwalls are an extension or continuation of the box walls. Wingwalls constructed in a line parallel to the roadway are commonly used to minimize right-of-way acquisition. Flared wingwalls shall be used where practical on the entrance ends of culverts for hydraulic reasons. Straight wingwalls may be specified when hydraulics and any additional costs are adequately considered.

The reference point for wingwall geometry is considered the intersection of the fill face of the wingwall and the exterior face of the box. The length of the wingwall is measured from the free end to the reference point along the fill face of the wall.

The length of walls shall be based on the roadway slope adjacent to the bridge. A 2:1 or flatter slope in front of the wingwall shall be used for the channel. The computed length of the wingwall shall be rounded up to the next 1 ft [300 mm]. The elevation at the end of flared wingwalls shall be computed from the flow line with a 2:1 slope and shall project at least 6 in [150 mm] above finished grade.

7.2.5 CUTOFF WALLS

Cutoff or toe walls shall be installed along the entrance and exit end bottom sides of all reinforced concrete box culverts when conditions dictate as directed in HEC-14. A typical cut off wall is shown in Figure 7-3. All structural plate pipe and structural plate box structures with full inverts shall have cutoff walls. Culverts without headwalls and cutoff walls used to drain ponds shall be fitted with anti-seep collars. The bottom of the cutoff wall shall meet the bottom of the wingwall footings.

7.2.6 SCOUR APRONS

Scour aprons are constructed of R-5 or larger riprap at both the inlet and outlet end of the culvert. The riprap placement is designed in accordance with HEC-14. Riprap in the stream shall be covered with a minimum of one foot [300 mm] of natural streambed material. Riprap on side slopes shall be topsoiled, seeded and mulched.

7.2.7 GUARDRAIL ATTACHMENTS

Guardrail is typically designed to span box or frame culverts less than 18 ft [5.5 m] wide without post support. For guardrail under an adequate depth of fill, posts should be driven as per standard guardrail installations. Where guardrail is used, the culvert shall be lengthened to account for dynamic deflection of the guardrail. For details, refer to DelDOT Standard Construction Details. In cases where culverts are more than 18 ft [5.5 m] wide and standard guardrail cannot be placed, a concrete parapet shall be constructed on top of the headwall. The standard guardrail-to-barrier connection should be used with concrete parapets within the clear zone. Designers shall refer to AASHTO's *Roadside Design Guide* for more information. Where possible, culverts should extend beyond the clear zone to eliminate the need for guardrail and parapets.

7.2.8 MISCELLANEOUS

The following additional criteria shall be considered in the design of culverts:

- It is desirable to skew culverts as required to match the stream alignment.
- Selection of a culvert type should be based on life-cycle cost analysis. A sample life-cycle cost analysis is contained in *Technical Release GL-88-2, Life Cycle Cost for Drainage Structures,* US Army Corps of Engineers.
- No more than three barrels should be constructed at a single location. Wider rows of cells are undesirable because of the increased maintenance they create due to debris build-up. Single-barrel culvert designs are preferred.
- When two or more single-barrel RCB's are abutting, a monolithic headwall shall be provided at each end to join the adjacent longitudinal barrels.

7.3 CONCRETE CULVERTS

Concrete culverts used by DelDOT include precast and cast-in-place boxes, rigid frames, arches, and pipes.

7.3.1 MATERIALS

All concrete for precast concrete culvert construction shall meet f'_c equals 5,000 psi

[35 MPa]. All other concrete shall be class A concrete and meet f'_c equals 4,500 psi [30 MPa].

Reinforcing steel meeting the requirements for AASHTO M31, Grade 60 [M31M, Grade 420], shall be specified. The minimum size of reinforcement for CIP concrete is a number 5 [16] bar. Welded wire fabric is permitted for reinforcing precast concrete sections with approval of the Bridge Design Engineer. All reinforcing steel shall be protected with fusion-bonded epoxy. Epoxy coating conforming to AASHTO M284 [M284M] shall be specified.

Concrete culverts should be treated with a silene sealer before backfilling. Geotextile fabric or wrap shall be placed over joints to prevent loss of fill material.

The minimum thickness of concrete for rigid frame components is 8 in [200 mm].

The minimum cover over rebar is 2 in [50 mm] on both sides.

7.3.2 DESIGN

Structural design of RCB culverts shall be carried out in accordance with the *AASHTO Specifications*, Section 12, Buried Structures and Tunnel Liners, and shall be analyzed and designed as rigid frames. When the depth of fill exceeds 8 ft [2.4 m], live load is ignored. The minimum top and bottom slab thickness is 8 in [200 mm]. Minimum wall thickness is 8 in [200 mm].

All cells of multiple-cell RCB culverts shall be the same size. The minimum height of RCB culverts is 4 ft [1.25 m] vertical clearance to allow for inspection. Four-sided boxes can typically be used for spans up to 12 ft [3.5 m]. Span lengths from 12 ft to 25 ft [3.5 m to 7.5 m] are typically bridged using three-sided rigid frames. Designers must consider the maximum size limitations for precast units. Limitations for shipping precast concrete sections are controlled by their size and weight. The maximum allowable weight of precast sections is 20 tons [18 metric tons].

The Department will usually accept alternative designs that meet specified design criteria. Alternate construction methods must be submitted to the Department for review and approval. Alternate method submittals must contain detailed drawings and calculations sealed by a professional engineer licensed in the state of Delaware.

7.3.3 REINFORCED CONCRETE BOX CULVERTS

The standard designation for the size of an RCB culvert shall be the span followed by the rise. Span and rise are measured from the inside wall dimensions. The designation for a multiple- cell RCB culvert shall be the number of cells followed by the cell size.

7.3.3.1 Precast Box Culverts

In most cases, the Department designs culverts as precast sections. The joint exterior shall be covered with a minimum of a 9” 225 mm] wide wrap centered on the joint. The wrap material shall comply with ASTM C877 or Petrolac, Phillips Fiber Corp. All joints between precast sections shall be tongue and groove. Precast units shall be constructed with lifting devices to pick up the sections, and pulling holes to pull the sections together.

Precast box sections may pull apart during or after construction if they are not contained. To prevent this, four longitudinal ½ in [12.7 mm] diameter, 270 ksi [1862

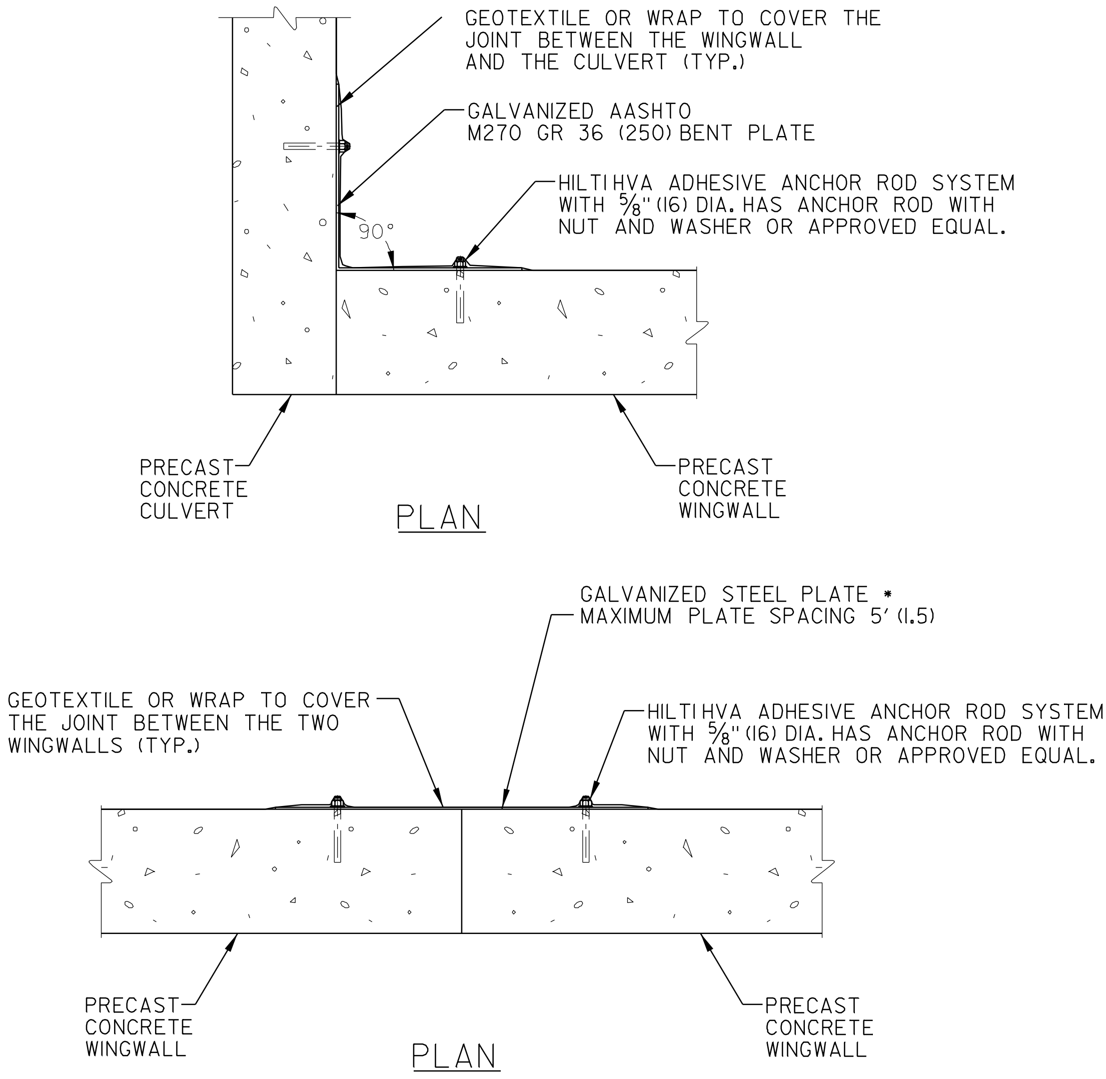
MPa] low relaxation polypropylene-sheathed prestressing strands with corrosion inhibitor or other approved post-tensioning device, shall be placed in position through preformed holes in the corners of the precast units. These sheathed prestressing strands shall then be stressed to a total tension of 31 kips [137 kN]. These end anchorage forces must be considered in the box culvert design. The minimum ultimate strength of each sheathed prestressing strand is 41 kips [183 kN]. After post-tensioning, the exposed end of the sheathed prestressing strand shall be removed. No part of the strand or the end fittings shall extend beyond a point 2 in [50 mm] inside the hand-hold pocket. The pocket shall then be filled with non-shrink grout. See Figure 7-5.

When the top slab of a precast culvert is specified as the riding surface, an asphalt-impregnated waterproof membrane shall be placed and the culvert shall be overlaid with 2 in [50mm] of hot-mix minimum.

7.3.3.2 Cast-In-Place Box Culverts

Cast-in-place culverts are occasionally designed when site conditions are not conducive to heavy equipment or when there are utility conflicts.

Figure 7-2
Wingwall to Culvert and Wingwall to Wingwall Connection Details



* - PLATE SHALL NOT BE DESIGNED AS A STRUCTURAL SUPPORT FOR THE WINGWALL. THE WINGWALL SHALL BE SELF-SUPPORTING. A MINIMUM OF TWO BOLTS SHALL BE INSTALLED ON EACH SIDE OF OF THE JOINT.

Figure 7-3
Typical CIP Cutoff Wall

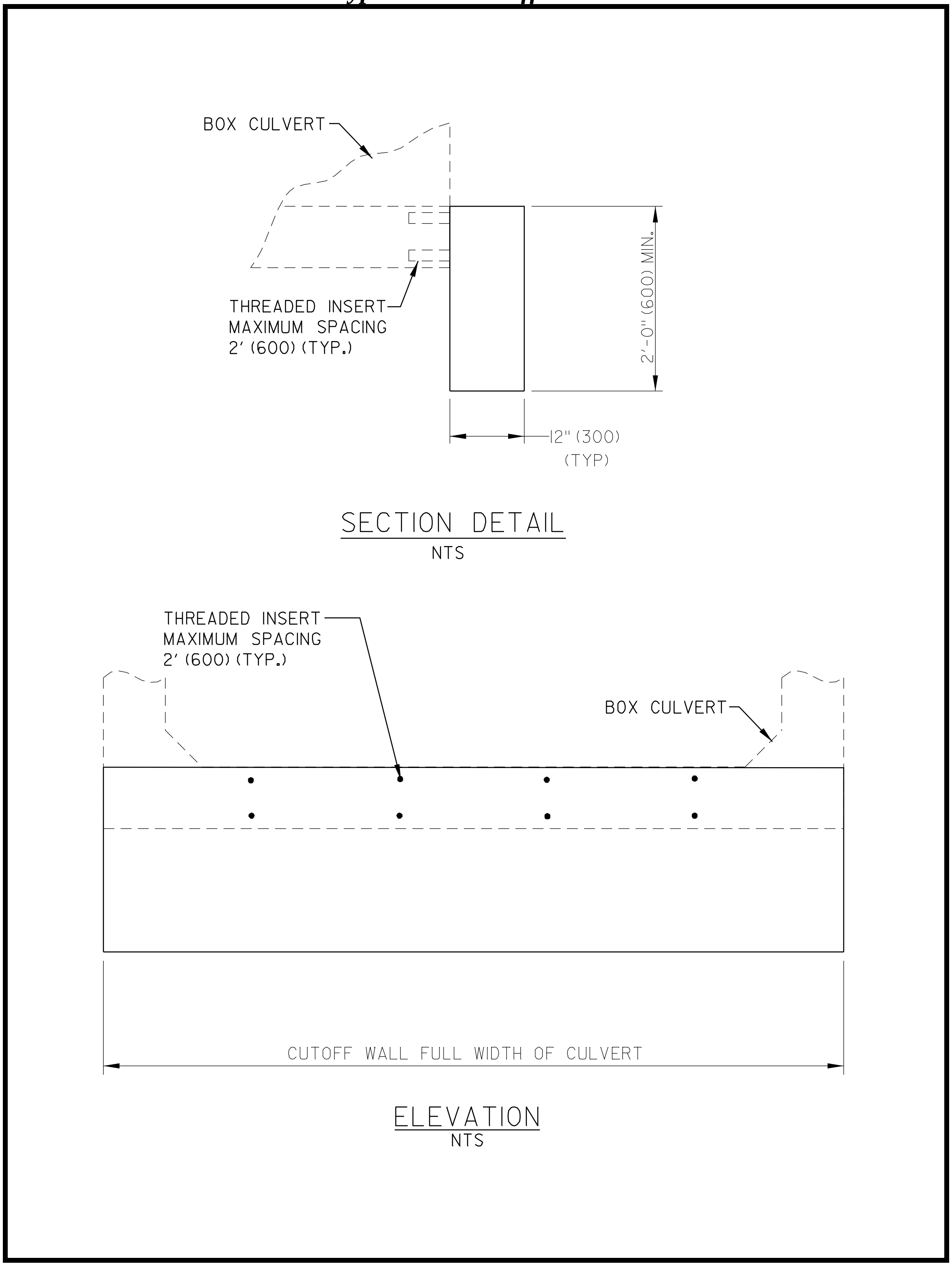
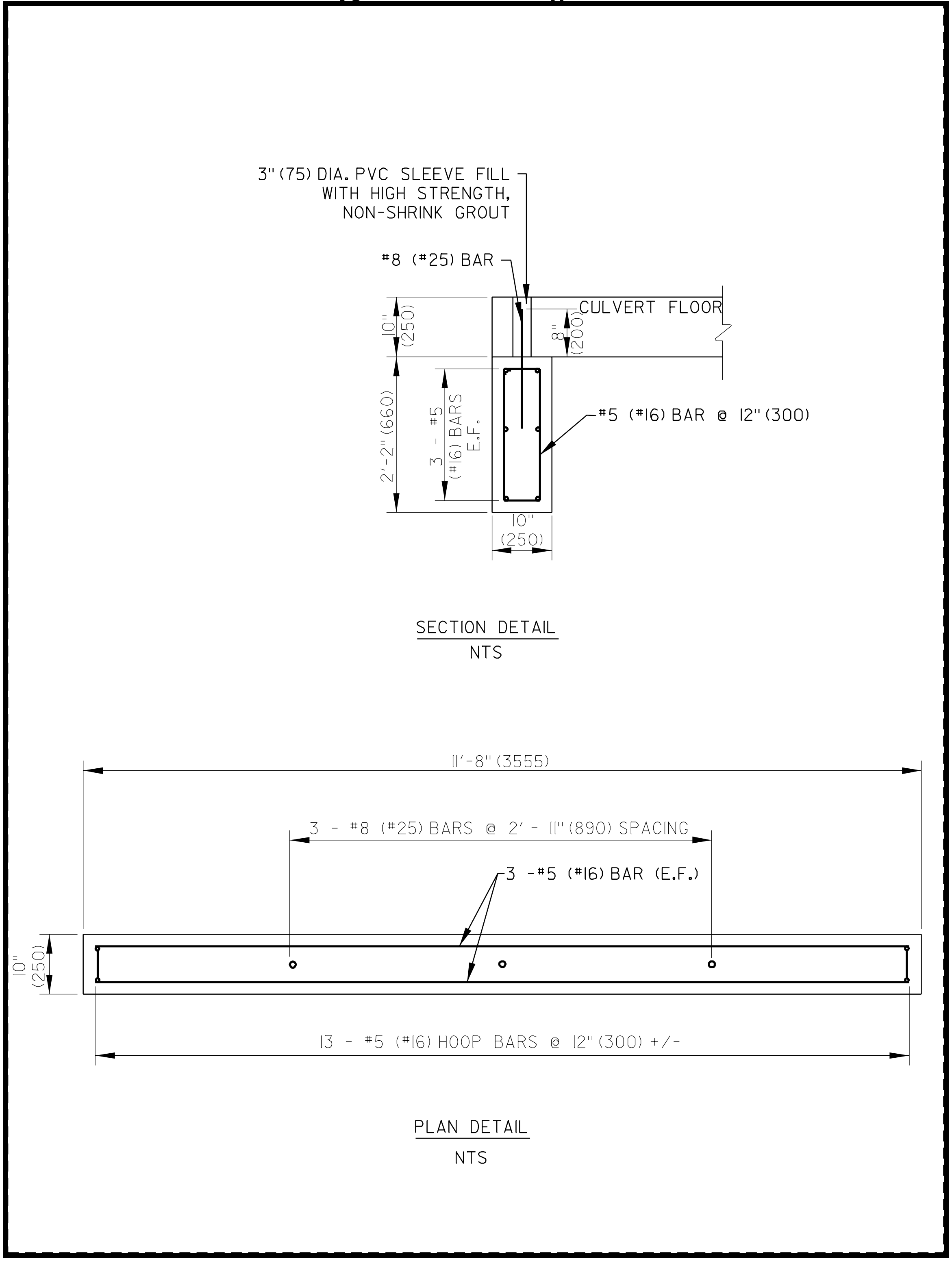


Figure 7-4
Typical Precast Cutoff Wall



7.3.4 RIGID FRAMES

Rigid frames are three-sided concrete structures placed on precast or cast-in-place footings without a paved invert. (See Figure 7-6.) Rigid frame structures are used to span streams and seasonal waterways where a natural streambed is desirable and preferred for environmental reasons. Rigid frames are typically used for spans ranging from 13 feet [4 m] to 25 feet [8 m].

Rigid frames may be cast in place or precast. Generally, the use of precast rigid frame sections can expedite construction to reduce the inconvenience to the traveling public. There are two types of rigid frames:

- rectangular
- arch

Normally, the Department designs rectangular rigid frames. Arch rigid frames are proprietary designs and may be considered with the approval of the Bridge Design Engineer. Refer to Section 7.3.6.

Refer to Section 3 (Loads and Load Factors) and Section 5 (Concrete Structures) in the *AASHTO Specifications* for design requirements.

Typically, rigid frames support earth fills or hot-mix wearing surfaces, depending on the location and profile grade with respect to the top of the frame. An overlay is required for precast but not for cast-in-place rigid frames.

The following must be considered when the wall height for rigid frame structures is determined:

- size of opening to meet the hydraulic requirements;
- transportation costs of prefabricated elements;
- transportability of the elements; and
- clearance for inspection, especially for flowing streams.

A haunch is required where the wall and slab join. The minimum size is 6 in [150 mm] by 6 in [150 mm]. Larger haunches, up to a maximum of 12 in [300 mm] by 12 in [300 mm], are permitted but must be reinforced.

Depending on site conditions, rigid frames may be placed on:

- cast-in-place spread footing,
- pile-supported, cast-in-place footing, or
- precast spread footing.

Holes are formed in precast frames to allow placement of tie rods or post-tensioning strands to hold adjacent rigid frame sections together. Tie rods shall be tensioned. Shear keys transfer shear between adjacent sections. Shear keys are sealed by filling with high-strength, non-shrink grout. (See Figure 7-7.)

Figure 7-5a
Post Tensioning Components Details

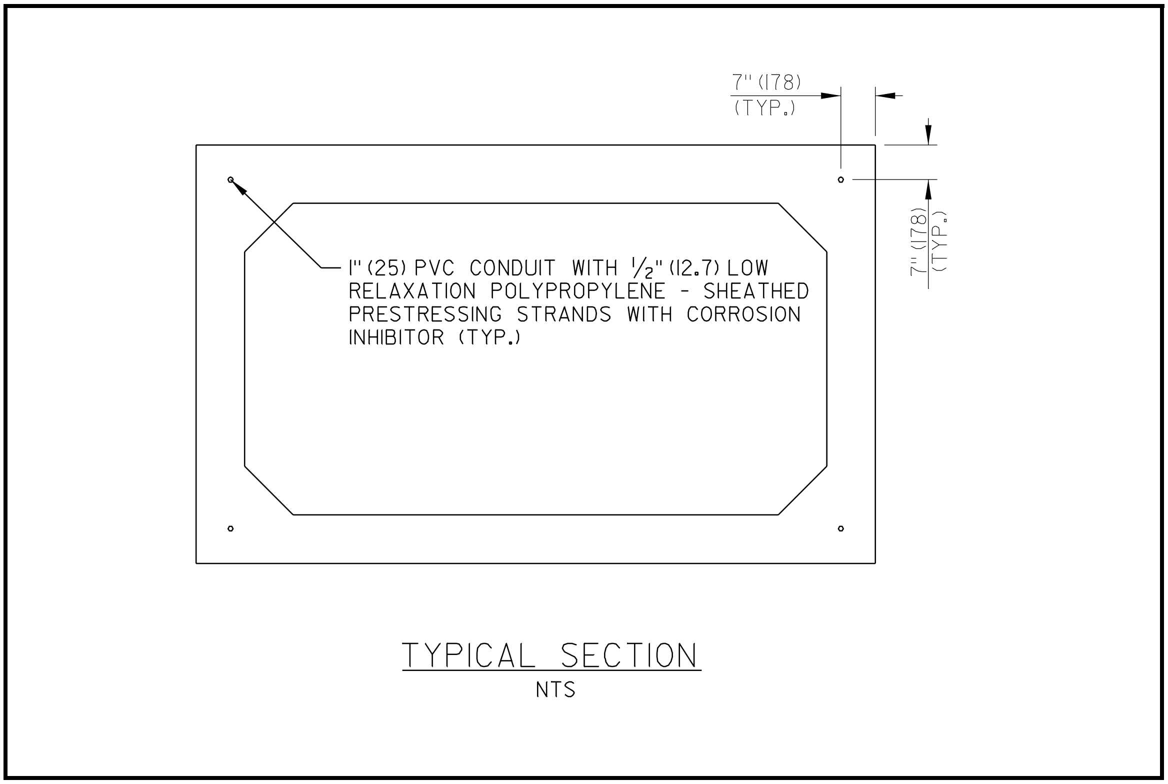
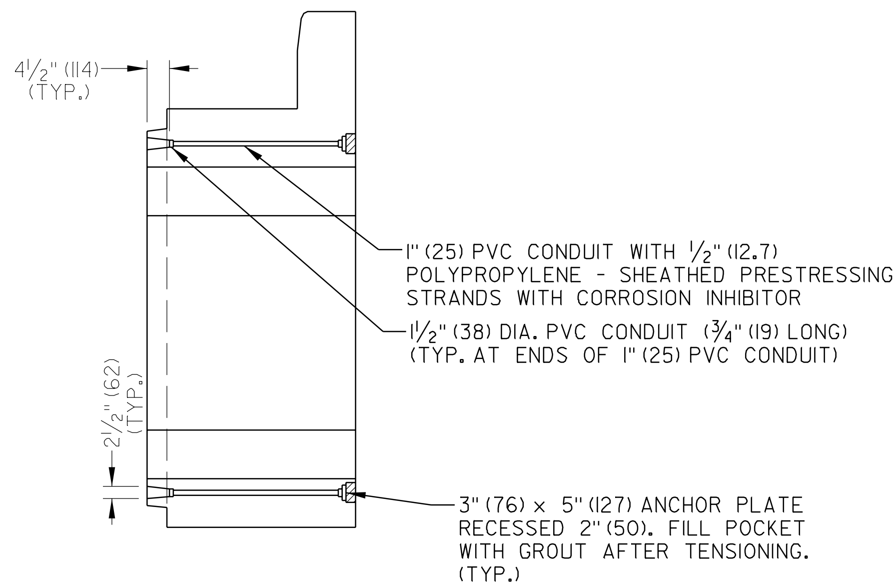
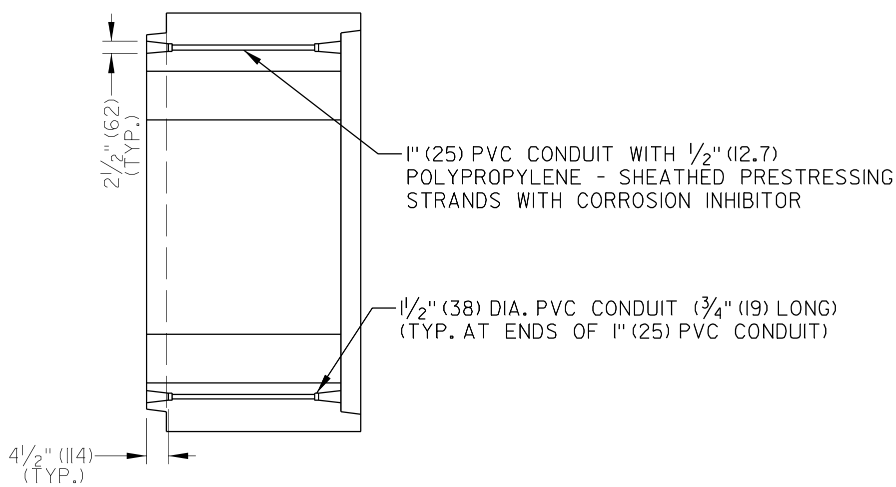


Figure 7-5b
Post Tensioning Components Details



ELEVATION VIEW



ELEVATION VIEW
SCALE NTS

Figure 7-6
Rigid Frame Detail Example

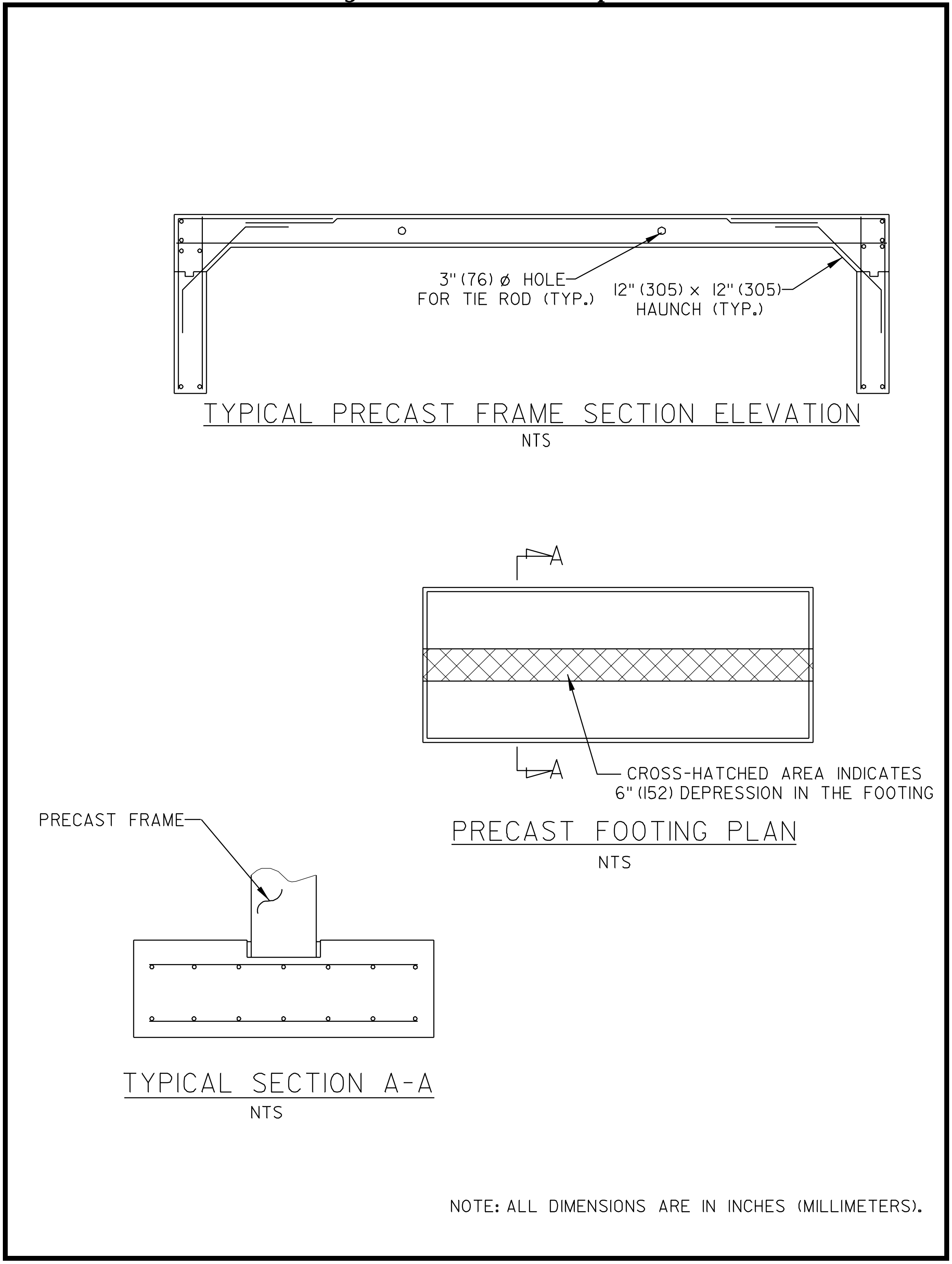
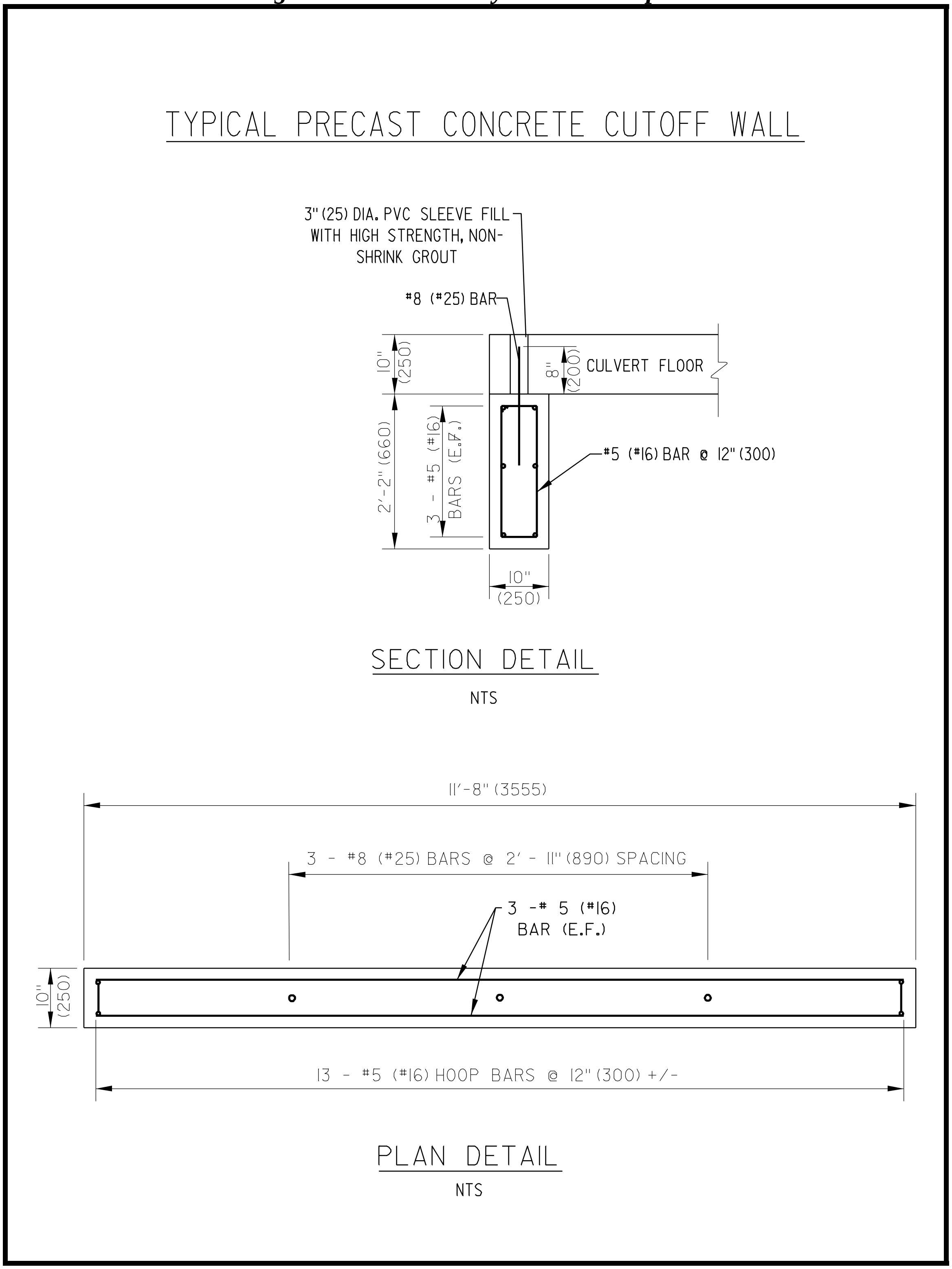


Figure 7-7
Rigid Frame Shear Key Detail Example



7.3.5 CONCRETE PIPE CULVERTS

Round and elliptical pipes are widely used for roadway drainage. They are standardized structures, and no structural drawings are needed in the contract documents. Design, material, manufacture, and testing requirements shall be in accordance with the Department's *Standard Specifications* and with the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*. This reference also provides the standard sizes of round and elliptical concrete culverts that are produced. Elliptical pipes used by the Department are normally horizontally elliptical.

7.3.5.1 Material

Materials for round and elliptical concrete pipe shall meet the requirements of *Standard Specifications*, Section 612 and *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, M170 (Round RCP) and M207 (Elliptical RCP).

7.3.5.2 Design

Concrete pipes are classified according to their construction and strength as class I, II, III, IV, or V. The standard pipe class used by DelDOT is class III. Class IV and V pipe shall be used when higher strength is needed. Selection of the class of pipe required is based on the diameter and height of fill above the top of the pipe.

Only round and elliptical concrete pipe culverts designed in accordance with *AASHTO Specifications*, Section 12, Buried Structures and Tunnel Liners, shall be used. Earth loads and live loads shall be in accordance with *AASHTO Specifications*, Section 3.

7.3.6 CONCRETE ARCHES

Concrete arches are typically used to accommodate long span and low rise site requirements. Typical concrete arch spans range from 30 to 50 feet [9 to 15 m]. Concrete arches are used to span streams and seasonal waterways where a natural streambed is desirable and preferred for environmental or aesthetic reasons.

All new concrete arches are precast. Extensions of existing arches may be cast in place.

7.3.6.1 MATERIALS

All concrete for the precast portion of concrete arches will meet f'_c equals 5,000 psi [35 MPa]. All other concrete will meet f'_c equals 4,500 psi [30 MPa].

Reinforcing steel meeting the requirements for AASHTO M31, Grade 60 [M31M, Grade 420], shall be specified. The minimum size of reinforcing bar for CIP concrete is #5 [16] bar. Welded wire fabric is permitted for reinforcing concrete arches with approval of the Bridge Design Engineer.

All reinforcing steel shall be protected with fusion-bonded epoxy. Epoxy coating conforming with AASHTO M284 [M284M] shall be specified.

7.3.6.2 DESIGN

Refer to Section 5, Concrete Structures, and Section 12, Buried Structures and Tunnel Liners, in the *AASHTO Specifications*. The design procedures in Section 5 apply for design of concrete arches where soil interaction is not considered. Soil interaction is considered only where the arch is poured monolithically with the footing. In this case, use the procedures in Section 12.

Two mats of steel are used in concrete arches. Concrete arches should be damp-proofed before backfilling.

7.3.6.3 THICKNESS

The minimum thickness for concrete arches is 8 in [200 mm].

7.3.6.4 CONCRETE COVER

The minimum cover over reinforcing steel is 2 in [50 mm] on the top and bottom of the arch.

7.3.7 PRECAST PROPRIETARY STRUCTURES

Precast proprietary structures may be proposed by contractors as alternatives to Department-prepared designs of rigid frame or concrete arches. Proprietary structures may be considered on a case-by-case basis and must meet the following requirements for approval:

- designed using the same AASHTO methods used by the Department;
- provide structural load rating using accepted methods;
- meet the specified minimum concrete strengths;
- furnish documentation of the structural strength of the structure including actual test results;
- provide documentation of long-term service to show durability; and
- provide connection between units.

7.4 METAL CULVERTS

Metal culverts used by the Department are corrugated metal pipe, structural plate, and pipe arch.

Due to lower life cycle costs, only aluminum or aluminum-coated (aluminized) steel shall be allowed on the Department's metal culvert bridge projects. All materials shall meet the requirements of the Department's *Standard Specifications* Section 614, and *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Sections M-36 and M-219. All metal pipe sections shall be tied together with metal bands that meet the requirements of AASHTO M36.

Structural design of corrugated metal pipes shall be in accordance with the *AASHTO Specifications*, Section 12, Buried Structures and Tunnel Liners. Earth loads and live loads shall be in accordance with the *AASHTO Specifications*, Section 3.6.1.2.6, Distribution of Wheel Loads Through Earth Fills.

7.4.1 CORRUGATED METAL PIPES

Corrugated metal pipe for storm drainage applications is not approved under U.S., interstate and state routes but may be used outside pavement limits. All pipe, pipe placement, and backfill shall be in accordance with DelDOT *Standard Specifications* Section 614. Manning's n value shall be per the manufacturer's recommendations. Gauge of the pipe shall be per the manufacturer's recommendations for the depth of fill and loading.

7.4.2 STRUCTURAL PLATE PIPE STRUCTURES

Designers may select from a variety of manufacturers available. Shapes include elliptical arches of various radii, pipe, pipe-arch, and ellipse. Size and shape shall be based on hydraulic and site requirements. Geometry, materials, Manning's n value, and plate gauge shall be based on availability and manufacturer's design charts. Designers shall refer to manufacturer's design charts when preparing the plans.

The bottom is typically depressed to allow for natural filling. Structural plate pipe culverts shall be designed with headwalls, and those constructed with bottom plates shall have cutoff walls. Backfill shall meet manufacturer's recommendations or DelDOT Standard Specifications. Foundation design shall follow the requirements of Chapter Six of this manual, and measures shall be taken to protect the footing from scour.

The contractor shall submit shop drawings and calculations sealed by a professional engineer for Department approval. All erection and backfill shall be in accordance with the manufacturer's shop drawings.

7.4.3 STRUCTURAL PLATE BOX CULVERTS

Designers shall select the size, geometry, material, and plate gauge of structural plate box culverts. Size and shape shall be based on hydraulic and site requirements. Geometry, materials, Manning's n value and plate gauge shall be based on availability and manufacturer's design charts. Designers shall refer to manufacturer's design charts when preparing the plans. Structural plate culverts shall be designed with headwalls, and those constructed with bottom plates shall have cutoff walls. Backfill shall meet the manufacturer's recommendations or DelDOT *Standard Specifications* requirements. Foundation design shall follow the requirements of Chapter Six, and measures shall be taken to protect the footing from scour. See Section 7.2.6 for bottom requirements.

The contractor shall submit shop drawings and calculations sealed by a professional engineer for Department approval.

7.5 HIGH DENSITY POLYETHYLENE PLASTIC PIPES

High density polyethylene plastic (HDPE) pipe is acceptable for use on Department projects. Please refer to Department guidelines for installation requirements.

7.5.1 MATERIAL

Material properties and specifications shall be in accordance with *AASHTO Specifications*, Section 12.

7.5.2 DESIGN

Structural design of HDPE pipe shall be in accordance with *AASHTO Specifications*, Section 12. Earth loads and live loads shall be in accordance with *AASHTO Specifications*, Section 3.